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Earthworm populations of a restored landfill site

K. W. Judd and C. F. Mason

Department of Biology, University of Essex, Wivenhoe Park, Colchester, CO4 3SQ, U.K.

Summary. — *1.* Earthworm populations were studied in the soils of a landfill site one year, 4 years and 12 years after restoration with a shallow (40 cm) cover material. *Allolobophora chlorotica* and *Lumbricus rubellus* were the most numerous species on the two older sites, while *Lumbricus terrestris* and *Aporrectodea caliginosa* were also present. Earthworms were not found during routine sampling on the newest site, which had a low pH, but an application of formalin revealed lateral penetration of small numbers of *L. rubellus* and *A. chlorotica* 5 m into the site. Experiments showed that *L. terrestris* could survive but not reproduce in soils of pH 3. — *2. L. terrestris, L. rubellus* and *A. chlorotica* were found mainly in the top 10 cm of the soil, *A. caliginosa* regularly occurring down to 20 cm. Downward movements occurred in relation to soil moisture but earthworms were not recorded in the refuse below the cover material. — *3.* Earthworm distribution showed little relationship to soil structure and chemistry, probably because of the uniformity of the cover materials. Earthworm populations were little affected by treatments to promote numbers in field trials.

Key words: Landfill, earthworms

Introduction

Once a landfill site has been filled to capacity it is capped with a final covering of soil, the quality and extent of which will depend on the proposed afteruse of the site. The transportation and disturbance of landfill cover materials inevitably results in a poor soil structure and low fertility (Brockmann et al. 1980; Curry & Cotton 1983), a problem exacerbated by the use of low quality subsoils rather than topsoils for cover material. Similar difficulties are encountered in the reclamation of other derelict sites (Gemmell 1977; Bradshaw & Chadwick 1980).

Earthworms are well known as promoters of soil structure and fertility, so there have been many investigations of earthworm ecology on reclaimed land. Reviews have been provided by Lee (1985) and Davis (1986).

Brockmann et al. (1980) specifically considered the colonization of municipal landfill sites in West Germany. *Lumbricus rubellus* Hoff. and *Dendrobaena octaedra* (Sav.) were dominant during the 5 years following restoration while *Eiseniella tetraeda* (Sav.) was also common. Lateral immigration rates (4 m year^{-1}) appeared to be directly or indirectly limited by high concentrations of methane. The deeper burrowing lumbricids were largely absent. Davis (1986) found colonization to be highly variable on similar sites in the U.K., the degree depending as much on the nature of the cover material as on time since final spreading. *Lumbricus castaneus* (Sav.) and *Allolobophora chlorotica* (Sav.) were numerically dominant in the 8 years following restoration, worms being largely restricted to the superficial root mat, horizontal and deeper burrowers again being rare.

The present study examines the populations of earthworms on a landfill site in northeast

Essex. Sites restored one year, four years and twelve years prior to the study using shallow depths of low quality cover were sampled monthly over a year. Colonization by earthworms of the most recently restored site was assessed. Earthworm distribution was related to soil structure and chemistry while experiments were conducted on survival and reproduction at different pHs. The response of earthworms to various management techniques, aimed to promote their populations, was investigated in field trials.

Materials and Methods

The study was conducted at Martin's Farm Landfill Site, northeast Essex (National Grid Reference TM117177) in 1987 and 1988. The study area was quarried for sand and gravel before landfilling and covers 24 ha adjacent to coastal saltmarshes. Tipping of domestic refuse began in 1967.

Three sites within the study area were chosen which had been restored 12, 4 and one years previously. The sites were covered with subsoil to an average depth of 40 cm and allowed to vegetate naturally. The 12-year old site was a well-drained sandy loam of neutral pH and low organic content, densely vegetated with a species poor grassland. The 4-year old site had been restored with a shallow layer of clay loam over a slightly more compacted clay and was rich in organic matter, had a neutral pH but was prone to waterlogging. Dense tussocks of *Holcus lanatus* L. dominated the species poor vegetation. The one year old site was restored with a single layer of clay, with a pH of 3.2, and a poor organic content which was prone to waterlogging. The sparse vegetation was dominated by ruderals. Further information and a description of the invertebrate fauna is provided by Judd and Mason (1995).

Earthworms were collected from 20 m × 20 m plots on the three sites at monthly intervals from August 1987 to July 1988. On each sampling occasion 10 randomly positioned 25 cm × 25 cm turves were dug to a depth of 30 cm at each site. All turves were divided into 10 cm depths and placed in sealed polythene bags, a 50 g subsample being taken for the gravimetric measurement of soil moisture content. In the laboratory turves were stored for a maximum of 72 h at 4 °C before sorting.

Each 10 cm layer of soil was broken into several subsamples and washed over a series of increasingly fine sieves (10 mm, 5 mm, 2 mm, 1 mm). Subsamples were crumbled by hand while being sprayed with a jet of water. Worms and egg capsules were periodically extracted by careful handsorting of all sieve contents. Worms were preserved in 4% formalin before identification and counting. The reproductive status was noted and individuals were air-dried for 48 h and weighed.

Soil samples were taken in April 1988 at positions coinciding with earthworm samples, i.e. 10 samples per site each month. Samples were taken using an auger of semi-circular cross-section which was driven to a depth of 30 cm into the soil. The resulting cores were divided into three 10 cm lengths. Subsamples of 50 g were immediately removed to determine moisture content gravimetrically (Allen 1974). The remainder of the core was air-dried, ground and passed through a 2 mm sieve, the resulting powder being stored in sealed plastic bags. Soils were analyzed for pH, organic matter, and total C, N, P, K following methods in Allen (1974).

On the recently restored site the extent of earthworm movement into the site was studied in November 1987 by collecting samples at 0, 5, 10, 20 and 40 m from the boundary hedgerow along 7 transects. At each position vegetation was clipped from an area of 25 cm × 25 cm and 27 L of 0.5% formalin was applied in three aliquots of 9 L at 10 minute intervals (Satchell 1969). The earthworms collected in each 10 minute period were stored separately.

In August 1988, when conditions were dry, five pits of area 0.5 m^2 were dug at the 12 and 4-year old sites to expose the refuse. Formalin was applied as above to see whether the refuse had been colonized by earthworms.

Laboratory trials were conducted to determine how the acid soil at the recently restored site might influence the establishment of earthworms. Random samples of soil were taken from the site, air-dried, mixed and ground through a 4 mm sieve. Plastic pots (diameter 18 cm, depth 15 cm) were each filled with soil. Soil pH was adjusted by the addition of calcium hydroxide, the quantity required being determined by experiment, to give pH values of 4, 5, 6 and 7, each being replicted seven times. Seven control pots (pH 3) were not treated. Pots were provided with small drainage holes, allocated random positions on a covered outdoor platform and attached to an automatic watering system. After one week two clitellate *L. terrestris*, collected by digging at the 12-year old site, were added to each pot. All pots were fitted with plastic collars to prevent earthworms from escaping and provided with 15 g of dried grass clippings on the surface as a food supply. Pots were then left for 24 weeks but single replicates of each treatment were examined at 4 weeks and 12 weeks to ensure the continued presence of earthworms and the maintenance of soil pH. At the end of the experiment the remaining pot contents were carefully hand-sorted for earthworms, egg capsules collected and the soil pH re-measured.

Field trials were conducted to assess the effects of various soil management practices on earthworm abundance. Eighteen 2 × 2 m plots were laid out in three rows of six on the 12-year old site, all plots being 2 m distant from their neighbours. Three plots were dug over, the soil being disturbed down to the refuse. Three more plots received ammonium nitrate fertilizer, applied at a rate of 100 kg N ha^{-1}. Turves of 10 cm depth were removed from three further plots, inverted and replaced, to increase soil organic matter while minimizing soil disturbance. The remaining 9 plots were left undisturbed. Three acted as controls, three were inoculated with 300 *L. rubellus* and a further three with 600 *L. rubellus*, worms being obtained from a vermiculturalist (F. Nash, Saling, Essex). The treatments were commenced on 7th April 1986, worms being added below the surface of the vegetation mat on 12th April, this date being taken as the start of the trial. After 72 weeks worms were collected by a surface application of formalin to the central 0.5 m^2 of each plot.

Results

Table 1 shows the total number and weight of earthworms collected during the study on the 4 and 12-year old sites. No earthworms were collected from the one year old site. On the 12-year old site *Allolobophora chlorotica* accounted for 66% of all worms collected, while *Lumbricus rubellus* was the most numerous species on the 4-year old site, making up 53.8% of the total collection. *A. chlorotica* also accounted for the greater part of the weight of the collection on the 12-year old site, whereas on the 4-year old site *Lumbricus terrestris* L. made up the majaority of overall weight. Weight was not determined for the two very scarce species.

Fig. 1 illustrates the seasonal changes in earthworm numbers. *L. terrestris* and *A. chlorotica* were most numerous in late winter and early spring, while *Aporrectodea caliginosa* (Sav.) was most numerous in autumn. *L. rubellus* occurred at greatest densities in late winter and spring. Seasonal changes in biomass followed those in numbers. The population densities of *L. terrestris* and *L. rubellus* were significantly positively correlated with soil moisture content over the study period (Spearman rank correlation $rs = 0.74$, $p < 0.01$, $rs = 0.58$, $p < 0.05$ respectively for the 12-year old sites; $rs = 0.60$, $p < 0.05$, $rs = 0.78$, $p < 0.01$ respectively for the 4-year old site, $n = 12$). Densities of *A. chlorotica* and *A. caliginosa* varied independently of soil moisture content.

Immature, non-clitellate earthworms predominated in the populations. There were more clitellate individuals of *L. terrestris* and *A. chlorotica* from August through to April, the number falling markedly in late spring and early summer. In contrast there were more clitellate individuals of *A. caliginosa* in late winter and spring. Numbers of clitellate *L. rubellus* were greatest between February and July. The numbers of egg capsules recovered each month from samples is shown in Fig. 2. At both sites peak numbers occurred in

Table 1. Total numbers and air dry weight (g) of earthworms collected from soil at two landfill sites, August 1987 – July 1988

	12 year old site				4 year old site			
	No.	%	weight	%	No.	%	weight	%
Lumbricus terrestris	261	9.2	21.6	27.1	369	29.2	23.7	65.4
L. rubellus	398	14.0	5.3	6.7	679	53.8	6.6	18.2
L. castaneus	14	0.5	–	–	16	1.3	–	–
Allolobophora chlorotica	1874	66.0	40.2	50.6	119	9.4	4.2	11.6
Aporrectodea caliginosa	286	10.1	12.4	15.6	75	5.9	1.7	4.8
Eiseniella tetraedra	7	0.3	–	–	4	0.3	–	–

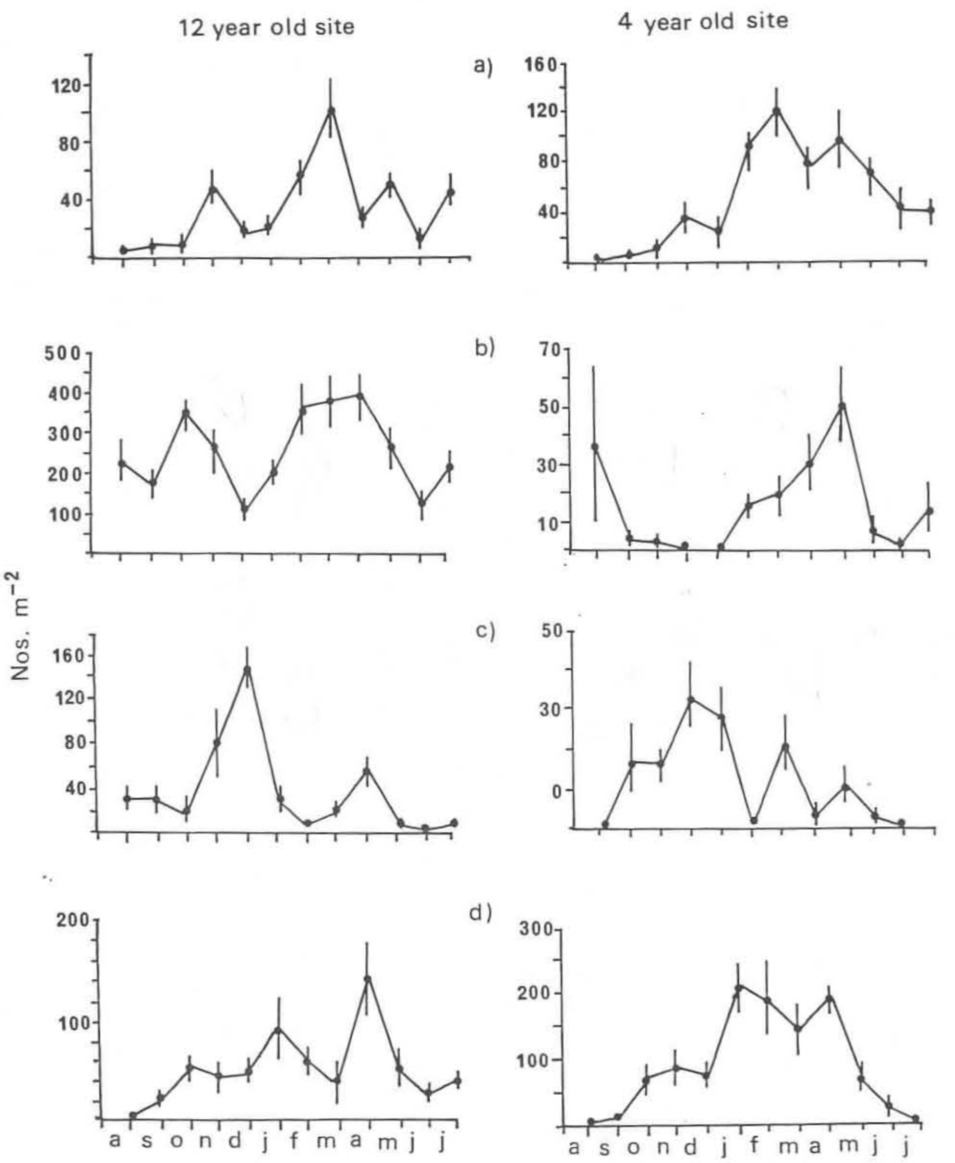

Fig. 1. Density (mean nos $m^{-2} \pm$ S.E.) of earthworms recorded each month, August 1987 – July 1988, on landfill sites twelve years and four years after restoration. a) *Lumbricus terrestris*, b) *Allolobophora chlorotica*, c) *Aporrectodea caliginosa*, d) *Lumbricus rubellus*

February. Most were recovered from the surface 10 cm of the soil (74% of the total at the 12-year old site, 92% of the total at the 4-year old site).

Over the study period as a whole less than 10% of the population of any species was found at a depth greater than 20 cm in the soil. On both sites more than 90% of *L. rubellus* and more than 70% of *L. terrestris* and *A. chlorotica* were present in the top 10 cm of the soil. On the 12-year old site *A. caliginosa* was more evenly distributed in the top 20 cm of the soil but 84% of the total from the 4-year old site were recorded in the top 10 cm. There were, however, some seasonal changes in depth distribution. Although at all seasons most individuals of *L. terrestris* remained in the top 10 cm of soil, 18% penetrated the 20 – 30 cm

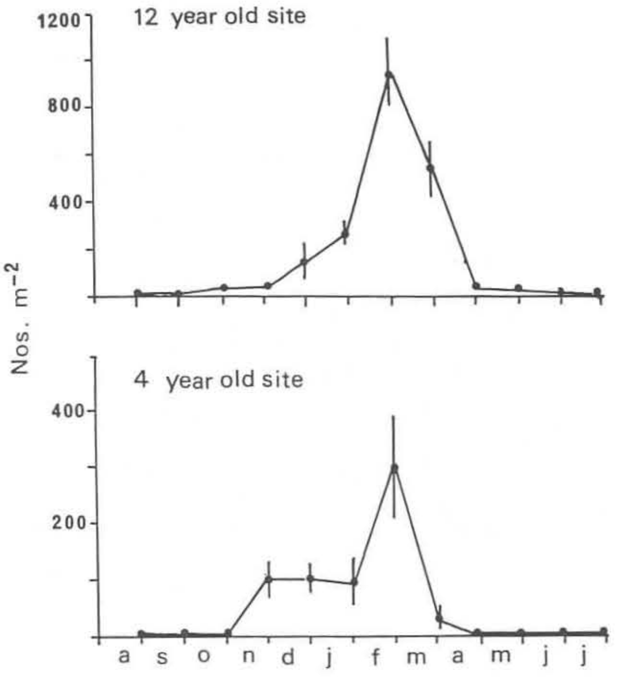

Fig. 2. Density (mean nos m^2 ± S.E.) of earthworm egg capsules recovered each month, August 1987 – July 1988, from the soil of landfill sites twelve years and four years after restoration

depth in the period May – July and the seasonal changes in distribution were significant ($\chi^2 = 25.5$, $p < 0.001$). A similar but less marked change occurred with *L. rubellus* ($\chi^2 = 12.9$, $p < 0.01$). *A. chlorotica* was more or less evenly distributed at the three depths from May – July ($\chi^2 = 18.3$, $p < 0.001$) and the majority of *A. caliginosa* were present at 20 – 30 cm depth in this period ($\chi^2 = 7.8$, $p < 0.05$), though this species was well represented in the 10 – 20 cm depth in all four seasons.

Earthworm distribution in April was examined in relation to soil parameters which were taken from the same sampling positions in that month. On the 12-year old site only *A. caliginosa* showed significant positive correlations with soil parameters, these being with carbon ($rs = 0.85$, $p < 0.01$) and total N ($rs = 0.83$, $p < 0.01$). These soil parameters were themselves positively correlated ($rs = 0.92$, $p < 0.001$). On the 4-year old site only *L. terrestris* showed significant positive correlations, with organic matter ($rs = 0.78$, $p < 0.01$), soil moisture ($rs = 0.79$, $p < 0.01$) and total N ($rs = 0.77$, $p < 0.01$). There were no significant correlations with P and K. There were no significant interspecific correlations in earthworm numbers.

The colonization of the newly restored one year old site was studied in November 1987 by sampling with formalin. All four species were present at the edge of the site. *L. rubellus* and *A. caliginosa* penetrated to 5 m into the site but numbers collected were only 20% and 8% respectively of those collected from the boundary. No earthworms were collected at 10 m, 20 m or 40 m from the boundary.

The refuse itself was sampled for earthworms using formalin at the two older sites in August 1988 when soil conditions were dry. No earthworms were recovered.

The results of the laboratory pH trials are summarized in Table 2. The pH values generally fell slightly over the period presumably because of leaching but the sequence of pH values was maintained. Of a total of 10 *L. terrestris* employed in each treatment, 10% were lost in soils adjusted to pH 4, 6 and 7 and 20% were lost in those adjusted to pH 3 and 5. However the final abundances were not significantly different ($F = 0.2$, $p > 0.05$, after

Table 2. Mean numbers of *Lumbricus terrestris* per pot (± S.E., n = 5) and egg capsules recovered after 24 weeks from soils in which pH had been adjusted

Initial pH	Final pH	Earthworms	Egg Capsules
3	3.12 ± 0.07	1.6 ± 0.4	0
4	3.47 ± 0.11	1.8 ± 0.2	0.2 ± 0.2
5	4.18 ± 0.25	1.6 ± 0.3	0.4 ± 0.4
6	4.71 ± 0.23	1.8 ± 0.2	0
7	5.83 ± 0.29	1.8 ± 0.4	12.6 ± 6.3

log transformation). Egg capsules were recovered in numbers only from the soil adjusted to pH 7, with isolated capsules in pH 4 and 5.

The results of the field trials are presented in Table 3. Analysis was restricted to *L. terrestris* and *L. rubellus*, studies of extraction methods having previously shown that only these species were effectively sampled using formalin (Judd 1989). Analysis of variance was carried out on log transformed data. Final *L. terrestris* numbers were independent of soil treatment ($F = 1.25$, $p > 0.05$). Numbers of *L. rubellus* did differ significantly between treatments ($F = 8.49$, $p < 0.01$), being significantly higher following soil disturbance and significantly lower following innoculation with 600 *L. rubellus* (Tukey fixed range test, $p < 0.05$).

Discussion

The earthworm communities of the two older sites were generally typical of temperate environments in that the number of species present usually ranges between 2 and 5 and population density between < 10 and ca. 400 m^{-2}, larger populations sometimes occurring in woodland and heavily fertilized pasture (Lee 1985). Species composition was characteristic of restored land in general (Curry & Cotton 1983) and reclaimed landfill in particular (Brockmann et al. 1980, Davis 1986). *L. rubellus*, *A. chlorotica* and *A. caliginosa* are three of the earliest and most successful colonists, their success being attributable to high reproductive rates and strong powers of dispersal (Curry & Cotton 1983). By contrast, lower reproductive rates (Evans & Guild 1948) ensure that *L. terrestris* is generally restricted to sites of greater age (Dunger 1969; Curry & Cotton 1983). Its occurrence on the 4-year old site was therefore unexpected (cf. Brockmann et al. 1980; Davis 1986); this and the large populations of other species suggest that they may have been introduced with the cover material (Davis 1986; Scullion et al. 1988). Natural dispersal may thus have played little part in the colonization of Martin's Farm by earthworms. Once introduced, local conditions will have determined the relative abundance of each species (Scullion et al. 1988). The dense root mat will have provided ideal conditions for *A. chlorotica* on the oldest site while *L. rubellus* will have been especially favoured by the moist, highly organic soils of the 4-year old site (Sims & Gerard 1985).

Table 3. Earthworm numbers (means ± S.E., n = 3) after 72 weeks in soils of different treatments and earthworm inoculations

Treatment	*Lumbricus terrestris*	*Lumbricus rubellus*
Fertiliser Application	11.0 ± 1.2	16.7 ± 2.7
Turf Inversion	11.0 ± 2.7	27.3 ± 5.5
Soil Disturbance	7.3 ± 4.3	47.3 ± 4.1
L. rubellus addition (300)	8.7 ± 1.2	15.3 ± 5.8
L. rubellus addition (600)	12.3 ± 2.6	4.0 ± 1.5
Control	12.0 ± 1.2	19.3 ± 3.4

The absence of earthworms from the major part of the recently restored site can be attributed to an initial paucity of earthworms within the original cover material, colonization therefore being entirely dependent on natural immigration. Natural immigration rates approximate to 5 m year^{-1} (van Rhee 1969; Brockmann et al. 1980; Marinissen & van den Bosch 1992). It is therefore significant that *L. rubellus* and *A. caliginosa* had penetrated 5 m onto this one year old area, despite the high acidity which is said to be detrimental to earthworms (e.g. Edward & Lofty 1977). The pot experiments revealed that *L. terrestris* was able to survive for prolonged periods in the acidic cover materials employed on this site, showing an unexpected tolerance in comparison with previous accounts. *L. terrestris* generally occurs in soils with a pH of between ca. 3.7 and 7.0 (Satchell 1955; Edwards & Lofty 1977) while the soils of this site had a natural pH of between 3.0 and 3.2. Nevertheless, substantial numbers of cocoons were recorded only from the soil of highest pH. The establishment of viable populations may therefore be unlikely within an acidic soil. Establishment could be improved by liming the cover material. Huhta (1979) found such an approach to be extremely effective in Scandinavian spruce forests. Results suggest that a final soil pH of 6 would be most beneficial though such large-scale liming operations could prove prohibitively expensive. Acidic cover materials should therefore be avoided wherever possible. Colonization might be greatly enhanced with the development of extensive plant cover and an associated root mat.

Seasonal variations in earthworm abundance and their distributions between the three sampling depths were ascribed to fluctuations in soil moisture content, this being a major determinant of earthworm activity (Evans & Guild 1948; Gerard 1967). Even surface dwelling species such as *L. rubellus* avoid adverse conditions of drought by becoming less active and staying deep within the soil (Lee 1985). The current study suggested that most species moved deeper in response to drier soil conditions. Even so, downward movement of all species, the deeper-working *L. terrestris* included, appeared to reach its lower limit at a depth of ca. 20 cm, few earthworms entering the 20 – 30 cm sampling depth and none penetrating the refuse itself. Vertical movements might be restricted by the compaction arising during soil-spreading (Blackwell et al. 1985), similar problems arising on land reclaimed from open-cast coal workings (Armstrong & Bragg 1984; Rushton 1986). Soil bulk densities below 20 cm depth (Judd 1989) were similar to those at which Rushton (1986) found *L. terrestris* unable to burrow during laboratory trials. This, in turn, suggests that the population declines of summer and winter arose from earthworm mortality rather than movement below the lower sampling depth, the numerical dominance of immatures indicating that subsequent recoveries were largely due to recruitment (Nowak 1975).

Patterns of seasonality were in close agreement with previously published accounts (Gerard 1967; Nowak 1975; Lee 1985), the constant presence of sexually mature individuals conforming to the description of earthworms as semi-continuous/continuous breeders given suitable conditions (Edwards & Lofty 1977). Capsules were deposited in greatest number during winter and spring, similar findings being reported on permanent pasture at Rothamsted (Gerard 1967). The age structures of all populations were similar to those reported by van Rhee (1965, 1969), numbers of immatures generally exceeding those of sexually mature individuals.

Attempts to identify those soil parameters influencing earthworm distribution were largely inconclusive, probably because of the uniformity of the cover materials. Soil organic matter, soil nitrogen and soil moisture produced the only meaningful relationships, these factors being known to influence earthworm distribution (Phillipson et al. 1976; Lee 1985).

Earthworm inoculations and soil management practices appeared to have little effect on the pre-existing earthworm fauna of the 12-year old site, the addition of 600 *L. rubellus* leading to a significant decline in abundance of this species, possibly because of intraspecific competition at a high population density. The addition of 300 *L. rubellus* failed to raise earthworm numbers relative to the control, inoculation therefore proving unsuccessful on soils with an established earthworm fauna. Large applications of organic nitrogenous fertilizer generally result in increased population densities, effects being particularly pronounced on surface-dwelling species such as *L. rubellus* (Edwards & Lofty 1982). Earthworms probably benefit from greater plant productivity and subsequent increases in the quantity of decomposing organic matter in such circumstances. One application was probably insufficient to raise earthworm numbers during the present study; better results may be achievable with annual applications over several consecutive years.

Regular cultivation generally depresses earthworm population density, though occasional incidents have little appreciable affect (Edwards & Lofty 1982). This may explain the results of the turf-inversion and soil disturbance trials on *L. terrestris*, though soil disturbance increased the number of *L. rubellus*. Earthworm populations would therefore be unlikely to be adversely affected by any soil disturbance arising during preparation for an amenity/conservation afteruse. Soil disturbance trials further indicated that soil compaction was not a limiting factor for earthworm survival, disturbance of the compacted layers failing to increase numbers of the deeper-working *L. terrestris*.

In conclusion, the earthworm communities of the 4 and 12-year old sites were typical of grassland sites. The most likely route of immigration was importation with the cover material. Natural immigration was comparable to that reported in previous studies, the evidence suggesting that uninoculated sites would be devoid of earthworms for quite a number of years, low soil pH further preventing the development of viable populations of *L. terrestris*. It is therefore suggested that cover materials are tested for earthworm content prior to their selection and that soils with a pH of <6 and which do not contain earthworms are avoided during site reclamation.

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